ICES SGCAL REPORT 2010

SCICOM STEERING GROUP ON ECOSYSTEM SURVEYS SCIENCE AND TECHNOLOGY

ICES CM 2010/SSGESST:11

REF. WGFAST, SCICOM, ACOM

Report of the Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal)

26–27 April 2010

San Diego, USA

ICES
International Council for the Exploration of the Sea
CIEM
Conseil International pour l'Exploration de la Mer

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

H. C. Andersens Boulevard 44–46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

Recommended format for purposes of citation:

ICES. 2010. Report of the Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal), 26–27 April 2010, San Diego, USA. ICES CM 2010/SSGESST:11. 20 pp.

Contents

Executive summary

The ICES Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal) convened its first meeting at the Hubbs SeaWorld Research Institute, West Room, in San Diego, California, USA, on 26 and 27 April, 2010. David Demer (USA) was Chair, and Neal Williamson (USA) was Rapporteur. Thirty scientists from ten nations participated (Annex 1). The agenda (Annex 2) spanned a day and a half, and, according to the terms of reference (Annex 3), included presentations on calibration-related developments and was focused on outlining a new Cooperative Research Report on the calibration of acoustic instruments (Annex 4). The following is a summary of the CRR outline, including names of **<u>lead</u>** and **contributing authors,** which was adopted:

1. SUMMARY **(<u>Demer</u>)**
2. LIST OF TERMS, SYMBOLS, AND UNITS **(<u>Demer</u>, Jech, Macaulay, Chu)**
3. INTRODUCTION **(<u>Jech</u>, Bethke, Demer, Weber, Fässler, Le Bouffant)**
    1. Acoustic theory **(Demer, Le Bouffant)**
    2. Signal processing theory **(Bethke, Le Bouffant)**
    3. Equipment
        1. Echosounders **(Weber, Lurton)**
        2. Transducer platforms **(Fässler)**
    4. Calibration methods **(Jech, LeBouffant)**
4. STANDARD SPHERE CALIBRATION **(<u>Macaulay</u>, Demer, Ryan, Scalabrin, Bethke, MacLennan)**
5. CALIBRATION UNCERTAINTY **(<u>Chu</u>, Demer)**
6. CALIBRATION PROTOCOLS **(<u>Williamson</u>, Parker-Stetter, Gauthier, Domokos, Le Bouffant, Demer, Korneliussen, Chu, Stienessen, Bernasconi, Melvin, Ryan)**
7. FUTURE WORK **(<u>Chu</u>, Melvin, Weber, Jech, Boswell, Ryan, Macaulay, Perrot, Lurton)**

A list of calibration-related references was compiled (Annex 5) and copies of most were distributed to members of the group.

The following timeline was adopted:

1 February 2011 – Draft chapters to section leads

1 March 2011 – Draft chapters to SGCal participants to review

April 2011 – Review chapters and collectively advise refinements

April 2012 – Review draft CRR

Sept 2012 – Submit final SGCal report and CRR

The next meeting will again be held in conjunction with WGFAST in Reykjavík, Iceland, from XX-XX XXXXX 2011.

1 Opening of the meeting

The ICES Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal) convened its first meeting at the Hubbs SeaWorld Research Institute, West Room, in San Diego, California, USA, on 26 and 27 April, 2010. David Demer (USA) was Chair, and Neal Williamson (USA) was Rapporteur.

Chair opened the meeting at 08:30 on 26 April with an invitation to participants to introduce themselves and their particular calibration interests. Chair praised the work by the 2007–2009 Topic Group on Acoustic Calibration of Echosounders (TGACE), Co-Chaired by Toby Jarvis (Australia) and Geir Pedersen (Norway). Lars Andersen (Norway) was recognized for his significant contributions to the TGACE report which details EK500 and EK60 algorithms.

Chair provided a list of calibration-related references (Annex 5) and called for additions. Chair solicited revisions to agenda. The proposed agenda was adopted.

2 Terms of Reference (ToR)

Chair called for review of the ToR. Discussions highlighted the following issues:

- Principal need for protocols to calibrate EK60, ES60 and ME70 echosounders;
- Need for standardized calibration metadata;
- Need for calibrated surface scattering data for seabed classifications; and
- Desire to calibrate hydrographic and water column multibeam systems.

The longevity of a new CRR was discussed considering the 25-year lifespan of CRR 144. The concept of a living document with "Wikipedia-like" add-ins was introduced, but no mechanism for doing so was finalized.

Recognized is the need to balance general principles of calibration with protocols for specific instrumentation.

The group agreed that estimates of bias and precision, both required and realized, should be an integral part of the document.

For acoustic systems with calibration protocols not currently available or well-defined, the group agreed to include discussion of general principles and future requirements.

Earlier proposed ToR were modified and adopted as in Annex 3.

3 Presentations to review recent calibration-related developments

Chair invited presentations to review recent calibration-related developments.

Toby Jarvis summarized results of 2007–2009 Topic Group on Acoustic Calibration of Echosounders (TGACE).

David Demer provided results of some recent work on the impact of water temperature on transducer performance. Findings support those detailed in Demer and Renfree (2009).

Tim Ryan provided some recent results 1) describing changes in gain with depth observed w/ Simrad's 38 and 120 deep-towed transducers, and 2) demonstrating consistency in point estimates of gain when calibrating a sphere at ranges of 8, 16 and 28 m. He noted that variance in measured sphere TS increased w/ range.

Lars Andersen mentioned that current research areas at Simrad include re-parameterization of LOBE to include new ways to estimate parameters. Also, Simrad is considering improved methods to estimate transducer equivalent beam angle.

Rudy Kloser presented results comparing seabed surface backscatter measured with EK500–38 system and an EM300 multibeam. He found differences of ~ 6 dB. These results emphasize the need for a procedure to calibrate EM system.

Naig Le Bouffant described recent results of ME70 sphere calibration in both bathymetric and water column mode and the impact of transducer roll while calibrating.

Dezhang Chu presented results using measures of passive noise in an SM20 multibeam to compare with ideal TVG curve.

4 Proposed outline for new CRR

Chair next reviewed topics list presented in CRR 144 (1987) and outline from TGACE by way of introduction to a discussion of his proposed outline for new CRR.

Taking into consideration ToR discussion, Chair posed question of whether to add surface backscattering strength (S_s) to volume backscattering strength (S_v) and target strength (*TS*) calibration. Group adopted this addition.

Group reached consensus that for instrumentation for which calibration protocols do not currently exist and for which expertise is not currently present in the group, discussion in the document will focus on general principles and current challenges.

In summary, Chair posed the idea of a "hybrid" document to include general principles of calibration for measurement of S_s, S_v, and *TS* with specific protocols offered for EK60, ES60 and ME70. If proffered, the group will consider additions to this list of specific instrumentation protocols.

The CRR outline (details in Annex 4), including names of lead and contributing authors, was adopted.

5 Timeline

The following timeline was adopted:

1 February 2011 – Draft chapters to section leads

1 March 2011 – Draft chapters to SGCal participants to review

April 2011 – Review chapters and collectively advise refinements

April 2012 – Review draft CRR

Sept 2012 – Submit final SGCal report and CRR

The first meeting of the SGCal was adjourned at 11:30 on 27 April 2010.

Annex 1: List of participants

Name		Country	Email
Andersen	Lars	Norway	lars.nonboe.andersen@simrad.com
Berger	Laurent	France	Laurent.Berger@ifremer.fr
Bernasconi	Matteo	Norway	matteo.bernasconi@imr.no
Bethke	Eckhard	Germany	eckhard.bethke@vti.bund.de
Börjesson	Patrik	Sweden	patrik.börjesson@fiskeriverket.se
Boswell	Kevin	United States	Kboswe1@lsu.edu
Chu	Dezhang	United States	Dezhang.Chu@noaa.gov
Condiotty	Jeff	United States	jeff.condiotty@simrad.com
Demer	David	United States	David.Demer@noaa.gov
Domokos	Réka	United States	Reka.Domokos@noaa.gov
Fässler	Sascha	The Netherlands	sascha.fassler@wur.nl
Gauthier	Stephane	New Zealand	gauthiers@niwa.co.nz
Higginbottom	Ian	Australia	ian.higginbottom@echoview.com
Hufnagle	Larry	United States	Lawrence.C.Hufnagle@noaa.gov
Jarvis	Toby	Australia	tobyj@myriax.com
Jech	Mike	United States	Michael.Jech@noaa.gov
Kloser	Rudy	Australia	rudy.kloser@csiro.au
Korneliussen	Rolf	Norway	rolf@imr.no
Larson	Niklas	Sweden	niklas.larson@fiskeriverket.se
Le Bouffant	Naig	France	Naig.Le.Bouffant@ifremer.fr
Lebourges-Dhaussy	Anne	France	Anne.Lebourges.Dhaussy@ird.fr
Lee	Kyounghoon	Korea	Khlee71@nfrdi.go.kr
Macaulay	Gavin	Norway	gavin.macaulay@imr.no
Melvin	Gary	Canada	gary.melvin@dfo-npo.gc.ca
Parker-Stetter	Sandra	United States	slps@u.washington.edu
Ryan	Tim	Australia	tim.ryan@csiro.au
Stienessen	Sarah	United States	Sarah.stienessen@noaa.gov
Taylor	Chris	United States	Chris.taylor@noaa.gov
Weber	Tom	United States	weber@ccom.unh.edu
Williamson	Neal	United States	Neal.Williamson@noaa.gov

Annex 2: Agenda – 2010 Meeting of SGCal

Monday, 26 April (Day 1)

08:30–08:50 **Opening**

- i. Greeting, introductions, and logistics
- ii. Selection of rapporteur
- iii. Review and adoption of agenda

08:50–10:30 Terms of Reference

- i. Review
- ii. Modify
- iii. Adopt

10:30–11:00 **Break**

11:00–12:30 Presentations to review calibration guides and references

- i. Measurement objectives
- ii. Calibration objectives
- iii. Acoustics Theory
- iv. Echosounder specifications
- v. Calibration methods
- vi. Uncertainty estimation

12:30–14:00 **Lunch**

14:00–15:30 Presentations to review calibration-related developments

- i. EK60, ES60, ES70, ME70, MS70, SX90, ES10, ADCP, DIDSON, ASL
- ii. Specifications
- iii. Theory
- iv. Techniques
- v. Apparatus
- vi. Uncertainty estimation

15:30–16:00 **Break**

16:00–17:30 Review and update draft CRR content and outline

- i. Content
- **ii.** Outline

Tuesday, 27 April (Day 2)

08:30–10:00 Agree on work to be completed before the 2011 SGCal meeting

- i. Identify tasks
- ii. Assign owners

10:30–11:00 **Break**

11:00–11:30 Identify major agenda items for the 2011 meeting of SGCal

- i. Review
- ii. Modify
- iii. Adopt
- iv. adjourn

Annex 3: SGCal terms of reference for the 2011 meeting

The **Study Group on Calibration of Acoustic Instruments in Fisheries Science** (SGCal), chaired by David A. Demer, USA will meet in Reykjavík, Iceland, from XX–XX XXXXX 2011 to:

a) Review, summarize, and report on the literature regarding:

i) Acoustic systems currently used in fisheries research and surveys;

ii) Theoretical principles of calibrating these instruments;

iii) Methods currently being practised; and

iv) Directions for future research.

b) Develop recommendations for methods to be used for acoustic system calibrations including:

i) Commonly used acoustic systems used in fisheries research and surveys;

ii) Principles of calibration, general, and specific to these selected systems;

iii) Standard protocols for calibrating these systems (e.g. quantitative system characterizations through to data collections and analyses); and

iv) Additional protocols needed.

c) Prepare a report for possible publication in the *Cooperative Research Report* series including:

i) Literature review of acoustic systems commonly used in fisheries science;

ii) Theoretical and practical principles of system calibrations of generic and selected instruments;

iii) Recommended protocols for calibrating generic and selected acoustic instruments used in fisheries science; and

iv) Future work.

SGCal will report by XX XXX 2011 (via SSGESST) for the attention of WGFAST, SCICOM and ACOM.

Supporting Information

Priority	Acoustic data are currently being collected from a variety of acoustic systems in many countries to address a range of ecosystem monitoring and stock management objectives. The ICES CRR covering this topic (CRR 144, Foote *et al.*, 1987) is now more than 20 years old. Although much of the theoretical principles are still relevant, some need to be expanded to include currently used technologies (e.g. multibeam and broadbandwidth systems), and methods and standard protocols for calibrating these instruments need to be updated. There exists an urgent need to evaluate this work and to develop recommendations for protocols appropriate to calibrations of acoustic systems used in fisheries research and surveys. This need has been identified by a number of ICES Member Countries and observer countries and has been conveyed to WGFAST and SSGESST.

Scientific justification	Action Item 1.10, 1.12.5, 1.14, 3.13 – a Action Item 1.13.1, 1.13.4, 1.13.5 – b Action Item 6.3 - c Term of reference a: The ICES reference for acoustic system calibrations needs review and revision to be useful to practitioners of fisheries acoustics for stock management. The first step in this process is to review, summarize and report on the literature regarding the acoustic systems that are currently used in fisheries research and surveys. The theoretical principles for calibrating these instruments must be capitulated, and the methods currently being practised must be evaluated. Term of reference b: Based the literature review, the Expert Group must make recommendations to the ICES community for standard protocols to be used for acoustic system calibrations. These protocols must cover the calibrations of all commonly used acoustic systems used in fisheries research and surveys, or be generic enough for calibrating other systems not specifically considered. The protocols must be practical and based on solid theoretical principles; and Term of reference c): There is a recognized need to comprehensively document the current theory and recommended practise of acoustic instrument calibrations for use in Fisheries Science, and publish them in an easily accessible report. WGFAST and SSGESST continue to recognize the difficulty of addressing these needs during full working group sessions and support the continuation of this Study Group composed of experts to develop recommended methods and guidelines without delay. This Study Group will meet three times.
Resource requirements	No new resources will be required for consideration of these topics at the relevant group meetings. Having overlaps with WGFAST meetings, this SG will draw on a larger resource pool of experts which will increases efficiency in completing the objectives and reducing travel costs.
Participants	It is expected that ca. twenty five scientists from six ICES and three observer countries will initially participate in the Study Group. History has shown this number will likely decline to about half that number as the meeting progress, and about one fourth may be active in authoring the report. Interested industry representatives, both hardware and software suppliers) should be actively invited to participate.
Secretariat facilities	None.
Financial	No financial implications. Having overlaps with other meetings of expert groups of SSGESST increases efficiency and reduces travel costs.
Linkages to advisory committees	There are no direct linkages to the advisory committees but the work is of relevance to ACOM.
Linkages to other committees or groups	No direct linkages, however, depending on the outcome organizations such as FAO will be interested in the results.
Linkages to other organizations	WGFAST. This work should have relevance to many working, groups carrying out stock assessment of many semi-demersal and pelagic species in many ICES countries.

Annex 4: Draft Cooperative Research Report Outline

1. **Summary (<u>Demer</u>)**
2. **List of Terms, Symbols, and Units (<u>Demer</u>, Jech, Macaulay, Chu)**
   - 2.1. Echo range
   - 2.2. Electro-acoustic efficiency
   - 2.3. Beam directivity
   - 2.4. Equivalent two-way beam angle
   - 2.5. Ambient Noise
   - 2.6. Self Noise
   - 2.7. Absorption coefficient
   - 2.8. Absorption loss
   - 2.9. Spherical spreading loss
   - 2.10. Refraction loss
   - 2.11. Attenuation
   - 2.12. Backscattering cross section
   - 2.13. Target strength
   - 2.14. Volume backscattering coefficient
   - 2.15. Volume backscattering strength
   - 2.16. Area backscattering coefficient
   - 2.17. Area backscattering strength
   - 2.18. Volume backscattering coefficient
   - 2.19. Volume backscattering strength
   - 2.20. Nautical area scattering coefficient
   - 2.21. Nautical area scattering strength
3. **Introduction (<u>Jech</u>, Bethke, Demer, Weber, Fässler, Le Bouffant, Lurton)**
   - 3.1. Acoustic theory **(<u>Demer,</u> Le Bouffant)**
     - 3.1.1. Power budget (Sonar theory, Radar theory, Combining two worlds)
       - 3.1.1.1. Transmit power
       - 3.1.1.2. Transducer efficiency
       - 3.1.1.3. Transducer directivity
       - 3.1.1.4. Echo range
       - 3.1.1.5. On-axis gain
       - 3.1.1.6. Attenuation
         - 3.1.1.6.1. Geometric spreading loss
         - 3.1.1.6.2. Absorption loss
       - 3.1.1.7. Area backscattering strength
       - 3.1.1.8. Effective receiving area
       - 3.1.1.9. Target strength (TS; dB re 1 m^2)
       - 3.1.1.10. Volume backscattering strength (S_v; dB re 1 m^{-1})
       - 3.1.1.11. Integrated volume backscattering coefficient (s_A)
       - 3.1.1.12. Biomass density (ρ; g-m^2)
       - 3.1.1.13. Surface scattering strength (S_s; dB re 1 m^2)
       - 3.1.1.14. Incidence angle (θ; º)
       - 3.1.1.15. Estimates of stochastic variables
     - 3.1.2. Signal processing theory (measurements)
       - 3.1.2.1. Echo range (r; m)
         - 3.1.2.1.1. Receiver delay
         - 3.1.2.1.2. Echo-pulse rise time
           - 3.1.2.1.2.1. Bandwidth

- 3.1.2.2. Target strength (*TS*; dB re 1 m^2)
- 3.1.2.3. Volume backscattering strength (S_v; dB re 1 m^{-1})
- 3.1.2.4. Integrated volume backscattering coefficient (s_A)
- 3.1.2.5. Biomass density (ρ; g-m^2)
- 3.1.2.6. Spatial reference
  - 3.1.2.6.1. Relative
  - 3.1.2.6.2. Geographic
- 3.1.3. Measurement-error function
  - 3.1.3.1. Accuracy (systematic error)
  - 3.1.3.2. Precision (random error)

3.2. Seabed classification
- 3.2.1. Power Budget
- 3.2.2. Measurements
  - 3.2.2.1. Surface scattering strength (S_s; dB re 1 m^2)
  - 3.2.2.2. Incidence angle (θ; º)
  - 3.2.2.3. Seabed type
  - 3.2.2.4. Spatial reference
    - 3.2.2.4.1. Relative
    - 3.2.2.4.2. Geographic
- 3.2.3. Measurement error function
  - 3.2.3.1. Accuracy
  - 3.2.3.2. Precision

3.3. Echosounders **(Weber)**
- 3.3.1. Single-beam
  - 3.3.1.1. Single-frequency
  - 3.3.1.2. Multi-frequency
  - 3.3.1.3. Broad bandwidth
- 3.3.2. Single-beam, split-aperture
  - 3.3.2.1. Single-frequency
  - 3.3.2.2. Multi-frequency
  - 3.3.2.3. Broad bandwidth
- 3.3.3. Multiple-beams
  - 3.3.3.1. Single-frequency
  - 3.3.3.2. Multi-frequency
  - 3.3.3.3. Broad bandwidth
- 3.3.4. Multiple-beams, split-aperture
  - 3.3.4.1. Single-frequency
  - 3.3.4.2. Multi-frequency
  - 3.3.4.3. Broad bandwidth

3.4. Transducer platforms **(Fässler)**
- 3.4.1. Vessels
  - 3.4.1.1. Hull-mount
  - 3.4.1.2. Keel-mount
  - 3.4.1.3. Pole-mount
  - 3.4.1.4. Towed-body
- 3.4.2. Autonomous vehicles
  - 3.4.2.1. Drifters
  - 3.4.2.2. Propelled vehicles
  - 3.4.2.3. Gliders
- 3.4.3. Stationary
  - 3.4.3.1. Buoys

- 3.4.3.2. Landers
- 3.5. Calibration methods **(<u>Jech</u>, Le Bouffant)**
  - 3.5.1. Standard sphere method
  - 3.5.2. Element vs. beamformed-data calibration
  - 3.5.3. Hydrophone reciprocity
  - 3.5.4. Self-reciprocity (echo from air-water interface)
  - 3.5.5. Impedance
  - 3.5.6. Inter-ship comparison
  - 3.5.7. Seabed echoes
  - 3.5.8. Self-calibrating methods
    - 3.5.8.1. Echo-integration and in-situ target strength
    - 3.5.8.2. Echo-counting
    - 3.5.8.3. Multi-scattering in a cavity
  - 3.5.9. Internal system tests and warnings (**Le Bouffant**)
    - 3.5.9.1. Continuous impedance measurements
  - 3.5.10. System-performance simulation (**Le Bouffant**)
  - 3.5.11. Factory calibration
    - 3.5.11.1. E.g., Biosonics
- 4. **Standard Sphere Calibration (<u>Macaulay</u>, Demer)**
  - 4.1. Materials
    - 4.1.1. Sphere targets
    - 4.1.2. Apparatus
      - 4.1.2.1. Sphere range
      - 4.1.2.2. Centering the sphere
  - 4.2. Method
    - 4.2.1. Measurements
      - 4.2.1.1. Hydrography
        - 4.2.1.1.1. Sound speed
        - 4.2.1.1.2. Absorption coefficient
      - 4.2.1.2. Equivalent Beam Angle
        - 4.2.1.2.1. Sound speed
        - 4.2.1.2.2. Mechanical angles
        - 4.2.1.2.3. Angle sensitivity
      - 4.2.1.3. Impedance
      - 4.2.1.4. Sphere *TS* vs. angular position
    - 4.2.2. Deeply deployed transducers **(<u>Ryan</u>, Macaulay, Scalabrin, MacLennan)**
      - 4.2.2.1. Towed bodies
      - 4.2.2.2. Cast echosounders **(MacLennan)**
        - 4.2.2.2.1. Real-time calibration
      - 4.2.2.3. AUVs
      - 4.2.2.4. Landers
  - 4.3. Results
      - 4.3.1.1. On-axis gain (*G*; dB re 1W)
      - 4.3.1.2. Beam directivity
        - 4.3.1.2.1. Beam widths
          - 4.3.1.2.1.1. Off-axis angles
        - 4.3.1.2.2. Equivalent two-way beam angle
      - 4.3.1.3. On-axis gain correction factor (*Sa*_corr; dB re 1W)
        - 4.3.1.3.1. Bandwidth effect
          - 4.3.1.3.1.1. Filter delay **(Bethke)**

5. **Calibration Uncertainty (<u>Chu</u>, Demer)**
    - 5.1. Accuracy (systematic error)
        - 5.1.1. Sphere target strength
            - 5.1.1.1. Theoretical prediction
            - 5.1.1.2. Material
                - 5.1.1.2.1. Properties
                - 5.1.1.2.2. Homogeneity
            - 5.1.1.3. Sphericity
            - 5.1.1.4. Temperature
            - 5.1.1.5. Pressure
        - 5.1.2. Bandwidth
        - 5.1.3. Receiver delay (filter delay)
        - 5.1.4. Linearity
        - 5.1.5. Dynamic range
        - 5.1.6. Equivalent beam angle
        - 5.1.7. Time-varied gain
            - 5.1.7.1. Sound speed
            - 5.1.7.2. Absorption
            - 5.1.7.3. Geometrical spreading
            - 5.1.7.4. Refraction
            - 5.1.7.5. Bubble attenuation
        - 5.1.8. Dynamic system performance
            - 5.1.8.1. Temperature
            - 5.1.8.2. Pressure
            - 5.1.8.3. Time
            - 5.1.8.4. Transducer biofouling
    - 5.2. Precision (random error)
        - 5.2.1. System stability
        - 5.2.2. Noise
    - 5.3. Error budget function
6. **Calibration Protocols (<u>Williamson</u>, Ryan, Parker-Stetter, Gauthier, Domokos, Le Bouffant, Demer, Korneliussen, Chu, Stienessen, Bernasconi, Melvin)**
    - 6.1. Simrad EK60, vessel-mounted, hull-mounted or retractable keel
        - 6.1.1. Single-beam, split-aperture
            - 6.1.1.1. Single-frequency protocol
            - 6.1.1.2. Multiple-frequency protocol
        - 6.1.2. Calibration Worksheet
            - 6.1.2.1. Metadata
    - 6.2. Simrad ES60, vessel-mounted **(<u>Ryan</u>, Williamson, Gauthier)**
        - 6.2.1. Single-beam
            - 6.2.1.1. Single-frequency protocol
            - 6.2.1.2. Multiple-frequency protocol
        - 6.2.2. Single-beam, split-aperture
            - 6.2.2.1. Single-frequency protocol
            - 6.2.2.2. Multiple-frequency protocol
        - 6.2.3. Calibration Worksheet
            - 6.2.3.1. Metadata
    - 6.3. Simrad ME70 / MS70 **(<u>Le Bouffant</u>, Demer, Korneliussen, Chu, Stienessen)**
        - 6.3.1. Multiple-beams, split-aperture, multiple-frequency, vessel-mounted
        - 6.3.2. Calibration Worksheet
            - 6.3.2.1. Metadata

6.4. Omnidirectional sonars (e.g. Simrad SH80 / SX90; **Bernasconi, Melvin)**
6.4.1. Multiple-beams, single-frequency, vessel-mounted
6.4.2. Calibration Worksheet
6.4.2.1. Metadata
6.5. ASL Water Column Profiler **(Ryan)**
6.5.1. Single-beam, buoy-mounted
6.5.1.1. Single-frequency protocol
6.5.1.2. Multiple-frequency protocol
6.5.2. Calibration Worksheet
6.5.2.1. Metadata

7. **Future Work** (**Chu, Melvin, Weber, Jech, Boswell, Ryan, Macaulay, Lurton)**
7.1. Emerging protocols
7.1.1. Echosounders
7.1.1.1. Simrad SM20/2000 **(Chu, Melvin, Perrot)**
7.1.1.2. Hydrographic sonars **(Weber, Lurton)**
7.1.1.3. Broad bandwidth sonars **(Jech, Chu)**
7.1.1.4. Sidescan sonars
7.1.1.5. ADCPs
7.1.1.6. Acoustic cameras **(Boswell)**
7.1.1.7. Simrad SX90
7.1.2. Deeply deployed transducers **(Ryan, Macaulay)**
7.1.2.1. Towed bodies
7.1.2.2. AUVs
7.1.2.3. Landers

8. **Conclusion**
9. **Acknowledgements**
10. **References**
11. **Appendices**
11.1. Equation for sound speed
11.2. Equation for absorption coefficient
11.3. Standard sphere target strengths

Annex 5: Calibration-related References

Beamiss, G. A., Robinson, S. P., Hayman, G., and Esward, T. J. 2002. Determination of the variation in free-field hydrophone response with temperature and depth. Acta Acustica – Acustica, 88: 799–802.

Bethke, E. 2008. Calibration_and_environment. On WGFAST Calibration Topic Group sharepoint site.

Blue, J. E. 1984. Physical calibration. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 184: 19–24.

Brierley, A. S., Goss, C., Watkins, J. L., and Woodroffe, P. 1998. Variations in echosounder calibration with temperature, and some possible implications for acoustic surveys of krill biomass. CCAMLR Science, 5: 273–281.

Bodholt, H. 2002. The effect of water temperature and salinity on echo sounder measurements. ICES Symposium on Acoustics in Fisheries, Montpellier June 2002 Paper No 123.

Byard, S. 1948. Note on the Impedance Variations of an Electro-Acoustic Transducer in a Reflecting Field, Proc. Phys. Soc., vol. 61, pp. 478–480.

Carstensen, E. L. 1947. Self-reciprocity calibration of electroacoustic transducers. Journal of the Acoustical Society of America, 19: 961–965.

Carstensen, E. L., Foldy, L. L. 1947. Propagation of Sound through a Liquid Containing Bubbles. Journal of the Acoustical Society of America, 19(3):481–501.

Chu, D., and Stanton, T. K. 1998. "Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton." Journal of the Acoustical Society of America, 104: 39–55.

Conti, S. G., Demer, D. A., Soule, M. A., and Conti, J. H. E. 2005. An improved multiple-frequency method for measuring in situ target strengths. ICES Journal of Marine Science, 62: 1636–1646.

Demer, D. A. 2004. An estimate of error for the CCAMLR 2000 survey estimate of krill biomass. Deep-Sea Research II, 51: 1237–1251.

Demer, D. A., and Hewitt, R. P. 1993. Calibration of an acoustic echo-integration system in a deep tank, with gain comparisons over standard sphere material, water temperature and time. SC-CAMLR Selected Scientific Papers, 9: 127–144.

Demer, D. A., Soule, M. A., and Hewitt, R. P. 1999. A multi-frequency method for improved accuracy and precision of *in situ* target-strength measurements. Journal of the Acoustical Society of America, 105: 2359–2376.

Demer, D. A., and Renfree, J. S. 2008. Variations in echosounder–transducer performance with water temperature. ICES Journal of Marine Science, 65: 1021–1035.

Doonan, I., Coombs, R., McClatchie, S. 2003. The absorption of sound in seawater in relation to estimation of deep-water fish biomass. ICES Journal of Marine Science 60 (5): 1047–1055.

Dragonette, I. R., Vogt, R. H., Flax, L., and Neubauer, W. G. 1974. Acoustic reflection from elastic spheres and rigid spheres and spheroids. II. Transient analysis," Journal of the Acoustical Society of America, 55: 1130–1137.

Dragonette, L. R., Numrich, S. K., and Frank, L. J. 1981. Calibration technique for acoustic scattering measurements," Journal of the Acoustical Society of America, 69: 1186–1189.

Foldy, L. L., Primakoff, H. 1945. A General Theory of Passive Linear Electroacoustic Transducers and the Electroacoustic Reciprocity Theorem. I. Journal of the Acoustical Society of America, 17(2): 109–120.

Foote, K. G. 1982. Optimizing copper spheres for precision calibration of hydroacoustic equipment." Journal of the Acoustical Society of America, 71: 742–747.

Foote, K. G. 1983. Maintaining precision calibrations with optimal copper spheres. Journal of the Acoustical Society of America 73: 1054–1063.

Foote, K. G. 1990. Spheres for calibrating an eleven-frequency acoustic measurement system." J. Const. Int. Explor. Mer, 46: 284–286.

Foote, K. G. 1991. Acoustic sampling volume. Journal of the Acoustical Society of America, 90: 959–964.

Foote, K.G. 1996. Coincidence echo statistics. Journal of the Acoustical Society of America, 99 (1): 266–271.

Foote, K. G. 2001. Calibrating a narrow band 18-kHz sonar. Woods Hole Oceanographic Institute contribution no. 10514.

Foote, K. G. 2006. Acoustic Robustness of Two Standard Spheres for Calibrating a Broadband Multibeam Sonar. Proc. Oceans 2006 MTS/IEEE, (Boston), 4pp.

Foote, K. G., MacLennan, D. N., 1984. Comparison of copper and tungsten carbide calibration spheres. Journal of the Acoustical Society of America, 75: 612–616.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., Simmonds. E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. Cooperative Research Report Const. Int. Explor. Mer, 144, 69 pp.

Foote, K. G., Naze, J., Tjotta, N., and Tjotta, S. 1987. Performance of the parametric receiving array: Effects of misalignment, 82(5): 1753–1757.

Foote, K. G., Atkins, P. R., Bongiovanni, C. C., Francis, D. T. I., Eriksen, P. K., Larsen, M., and Mortensen, T. 1999. "Measuring the frequency response function of a seven-octave bandwidth echo sounder." Proc. I.O.A., 21(1): 88–95.

Foote, K. G., Chu, D., Hammar, T. R., Baldwin, K. C., Mayer, L. A., Hufnagle, Jr., L. C., and Jech, J. M., 2005. Protocols for calibrating multibeam sonar, Journal of the Acoustical Society of America, 117 (4): 2013–2027.

Foote, K. G., Francis, D. T. I., and Atkins, P. R. 2007. Calibration sphere for low-frequency parametric sonars. Journal of the Acoustical Society of America, 121(3): 1482–1490.

Francois, R. E., and G. R. Garrison, 1982. Sound absorption based on ocean measurements, part 11: Boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America, 72: 1879–1890.

Furusawa, M. 1991. Designing quantitative echosounders. Journal of the Acoustical Society of America, 90: 26–36.

Hickling, K. 1962. Analysis of echoes from a solid elastic sphere in water. Journal of the Acoustical Society of America, 34: 1582–1592.

Jech, J. M., Foote, K. G., Chu, D., and Hufnagle, L. C., Jr. 2005. Comparing two 38-kHz scientific echosounders. ICES Journal of Marine Science, 62:1168–1179.

Knudsen, H. P. 2009. Long-term evaluation of scientific-echosounder performance. ICES Journal of Marine Science, 66: 1335–1340.

Korneliussen, R. J., and Ona, E. 2002. An operational system for processing and visualizing multi-frequency acoustic data. ICES Journal of Marine Science, 59: 293–313.

Mackenzie, K. V. 1981. Nine-term equation for sound speed in the oceans. Journal of the Acoustical Society of America, 70: 807–812.

MacLean, W. R. 1940. Absolute Measurement of Sound without a Primary Standard. Journal of the Acoustical Society of America, 12:140–146.

MacLennan, D. N. 1981. The Theory of Solid Spheres as Sonar Calibration Targets. Scottish Fisheries Research. 22. 17 p.

MacLennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365–369.

Mott, P. H., Roland, C. M., and Corsaro, R. D. 2002. Acoustic and dynamic mechanical properties of a polyurethane rubber. Journal of the Acoustical Society of America, 111: 1782–1790.

Nam, G. H., Cox, M. G., Harris, P. M., Robinson, S. P., Hayman, G., Beamiss, G. A., Esward, T. J., and Smith, I. M. 2007. A model for characterizing the frequency-dependent variation in sensitivity with temperature of underwater acoustic transducers from historical calibration data Meas. Sci. Technol. 18:1553–1562.

Neubauer, W. G., R. H. Vogt, and L. R. Dragonette, 1974. Acoustic reflection from elastic spheres. I. Steady-state signals." Journal of the Acoustical Society of America, 55: 1123–1129.

Nielson, R. L., I. Hampton, and I. Everson, 1980. Calibration of Hydro-acoustic Instruments. BIOMASS Handbook No. 1, SCAR/SCOR/IABO/ACMRR, 52 pp.

Ona, E., Mazauric, V., and Andersen, L. N. 2009. Calibration methods for two scientific multi-beam systems. ICES Journal of Marine Science, 66: 1326–1334.

Patterson, R. 1967. Using the ocean surface as a reflector for a self-reciprocity calibration of a transducer. Journal of the Acoustical Society of America, 42: 653–655.

Primakoff, H., Foldy, L. L. 1947. A General Theory of Passive Linear Electroacoustic Transducers and the Electroacoustic Reciprocity Theorem. II. Journal of the Acoustical Society of America, 19(1): 50–58.

Reynisson, P. 1990. A geometric method for measuring the directivity of hull-mounted transducers. Rapp. P-v. Reun. Cons. Int. Explor. Mer. 189: 176–182.

Reynisson, P. 1998. Monitoring of equivalent beam angles of hull-mounted acoustic survey transducers in the period 1983–1995. ICES J Mar Sci 55: 1125–1132.

Robinson, S. P., Harris, P. M., Ablitt, J., Hayman, G., Thompson, A., Lee van Buren, A., Zalesak, J. F., Drake, R. M., Isaev, A. E., Enyakov, A. M., Purcell, C., Houqing, Z., Yuebing, W., Yue, Z., Botha, P., Krüger, D. 2006, An international key comparison of free-field hydrophone calibrations in the frequency range 1 to 500 kHz. Journal of the Acoustical Society of America, 120(3): 1366–1373.

Sabin, G. A. 1956. Transducer calibration by impedance measurements. Journal of the Acoustical Society of America, 28: 705–710.

Sabin, G. A. 1964. Calibration of Piston Transducers at Marginal Test Distances. Journal of the Acoustical Society of America 36 (1): 168–173.

Sawada, K., and Furusawa, M. 1993. Precision calibration of echo sounder by integration of standard sphere echoes. J. Acoust. Soc. Japan. 14 (4): 243–249.

Simmonds, E. J. 1984. A comparison between measured and theoretical equivalent beam angles for seven similar transducers. J. Sound and Vibration. 97(1): 117–128.

Simmonds, E. J. 1990. Very accurate calibration of a vertical echo sounder: a five-year assessment of performance and accuracy. Rapp. P.-v Réun. Cons. int. Explor. Mer. 189: 183–191.

Simmonds, E. J., and MacLennan, D. N. 2005. Fisheries Acoustics: Theory and Practice, 2nd edn, Blackwell Publishing, Oxford. 437 pp.

Simrad. 2002 Non-linear effects: recommendation for fishery research investigations, News bulletin.

Simrad. 1993. Simrad EK500 Scientific Echo Sounder Instruction Manual. Simrad Subsea A/S, Horten, Norway.

Simrad–Kongsberg. 2003. Simrad EK60 Scientific Echo Sounder System, Simrad Subsea A/S, Horten, Norway. 102 pp.

Stanton, T. K., Chu, D. 2008. Calibration of broadband active acoustic systems using a single standard spherical target. Journal of the Acoustical Society of America 124 (1): 126–138.

Sun, Z., Gimenez, G., Vray, D., and Denis, F. 1991. "Calculation of the impulse response of a rigid sphere using the physical optic method and modal method jointly." Journal of the Acoustical Society of America, 89: 10–18.

Tichy, F. E., Solli, H., and Klaveness, H. 2003. Non-linear effects in a 200-kHz sound beam and the consequences for target strength measurement. ICES J. Mar. Sci. 60: 571–574.

Urick, R. J. 1983. Principles of Underwater Sound, 3rd edn. McGraw-Hill, New York.

Vagle, S., Foote, K. G., Trevorrow, M. V., and Farmer, D. M. 1996. A Technique for Calibration of Monostatic Echosounder Systems. IEEE Journal of Oceanic Engineering, 21(3): 298–305.

Van Buren, A. L., Drake, R. M., and Paolero, A. E. 1999. Temperature dependence of the sensitivity of hydrophone standards used in international comparisons. Metrologia, 36: 281–285.

Widener, M. W. 1980. The measurement of transducer efficiency using self-reciprocity techniques. Journal of the Acoustical Society of America, 67: 1058–1060. Erratum: 68: 706.

Wilson, O. B. 1988. Introduction to Theory and Design of Sonar Transducers. Peninsula Publishing, Los Altos, CA. 191 pp.

Yasuno, Y., Ohga, J. 2006. Temperature characteristics of electret condenser microphones, Acoust. Sci. and Tech. 27, 4.